

SIMULATION OF TUNNEL LINING AND SURROUNDING ROCK MASS RESPONSE TO CONSTRUCTION LOADS

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ABSTRACT

The major design parameters related in tunnel engineering are loads, tunnel dimensions, geological and geotechnical properties of the ground surrounding the tunnel, which controls stresses and deformation of this underground structure. The effects of static loads during tunneling with shield Tunnel Boring Machine (TBM) on the rock mass and segmental concrete lining are considered. Applied static loads are (self-weight, drilling or excavation pressure, jack thrust, shield external pressure and segment external pressure). A comparison of the results of maximum total displacement and principal stresses of soft rock for different tunnel diameters including (D = 4, 6, 8, 10, 12 and 14 m) is performed. Tunnel lining of a circle tunnel were assumed to behave in a simple linear elastic way. Rock mass is assumed to be Isotropic, homogeneous and elastic rock in this modelling. The numerical analysis has been simulated and evaluated for each models separately. The thickness of tunnel lining for all models was assumed as 30 cm. The main concluding points of this study are to analyze the behaviour of tunnel lining and the surrounding rock under static loads during the construction processes using numerical modeling.

KEYWORDS: Static load; Numerical modeling; Tunnel; Finite element method; Displacement; Stresses

1. INTRODUCTION

Tunnels are one of the complex and high-cost engineering structures, subjected to unexpected problems during the process of the construction, due to the geological and geotechnical conditions, construction technology, structure elements, etc. According to the tunnels construction, several points have been considered in the design, including tunnel dimensions, geological and geotechnical parameters, which act on its stresses and deformation response. Usually, the primary tunnel lining is use to resist all transient loads that pass during construction activities. The secondary lining is used to ensure a safe support of the tunnel for the any other additional loads (Kim, 1997). A segmental lining generally performs better than a continuous lining during

an earthquake (Dean et al., 2006; Power et al., 2004; Kaneshiro and Sinha, 2008). The presence of segment joints in a tunnel lining can reduce the stresses and strains in the lining (Hashash et al., 2001). In general, the increase of lining forces is a function of the stiffness ratio between the soil and the tunnel (e.g. Penzien & Wu, 1998). Franza and Marshall, (2019) studied the empirical and semi-analytical methods to evaluate tunnel structure in sandy soil. Minglun, et al., (2018) investigated the effect of earth pressure balance (EPB) shield with mid-shield-grouting on the settlement of existing structures. Penzien & Wu, (1998) presented an analytical procedure to evaluate the stresses in linings of bored tunnels caused by kinematic soil-lining interaction. El Naggari, et al. (2002) presented a closed-form solution for composite tunnel lining in a homogeneous infinite isotropic

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elastic medium. On other hand, authors used slip and no slip approach at the lining-ground interface to evaluate the moment and thrust. Khan, et al., (2017) limiting the surface and subsurface settlement and stresses in lining produced due to tunnelling in shallow and soft ground has been perceived as the main challenge of any geotechnical engineer. Wang, (2012) stated that one of the most important problems associated with tunneling is to determine the deformation produced by tunnel excavation. Numerical simulation using the MIDAS GTS NX (v. 2.1, 2015) is presented in order to analyze the behaviour of tunnel lining and the surrounding rock under static loads during the construction processes. The distribution of the principal stresses and displacement including the maximum value are evaluated and used in different comparisons.

2. NUMERICAL MODEL

2.1 Definition of Ground and Structural Material

The thickness of concrete lining and tunnel depth from the ground surface are fixed on $t = 0.3\text{m}$ and $h = 20\text{m}$ respectively. The ground medium is considered as an elastic single soft rock layer. The input material and properties of ground and structure units used as input data are summarized in Tables (1-3). The cubic geometry of the subsurface model profile that used for each models has the same dimensions $x = 100\text{ m}$ of width, the height is $z = 100\text{ m}$ and the length of tunnel is $y = 80\text{ m}$, all models has the same

geometry. Automatically ground boundary condition has been used. Applied static loads including gravity, drilling or face excavation pressure 0.2 MPa that is applied on the shield excavation face, the jack thrust 4.5MPa that is applied on the previous segment face in the longitudinal direction, the shield external pressure 0.05MPa and segment external pressure 1 MPa that are applied around the tunnel (MIDAS Information Technology).

Table (1): Mechanical parameters that used in the model

Name	Soft Rock	Segment
Material	Isotropic	Isotropic
Model Type	Elastic	Elastic
Elastic Modulus (E) [MPa]	20	20000
Poisson's Ratio (ν) [-]	0.4	0.2
Unit Weight (γ) [kN/m^3]	18	24

Table (2): Mechanical parameters of the tunnel

Name	Steel	Grout
Material	Isotropic	Isotropic
Model Type	Elastic	Elastic
Elastic Modulus (E) [MPa]	250000	15000
Poisson's Ratio (ν) [-]	0.25	0.3
Unit Weight (γ) [kN/m^3]	78	23

Table (3): The FE types of rock and construction parts of model

Material	Rock	Segment	Steel	Grout
Type	3D	3D	2D- Plate	2D - Plate

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2.2 Static Load and Pressure

There are several loads effects on tunnel through construction process. An external axial load it called jack thrust, which pushed the shield forward in the excavation direction. Grouting pressure is other external force that acts along the tunnel wall. Grouting employed to minimize and/or prevent deformation from the ground surrounding tunnel. In general, increasing the grouting load leads to increase the effective stresses on tunnel lining, thus increase the overall overburden stresses. Figure 1 shows screenshots of definitions static pressures using MIDAS GTS NX software. The static pressures are set on the face or edge of a plate element, plane stress element or solid element. In MIDAS GTS NX, the input pressure is applied as distributed force for an element face or edge in various axis directions.

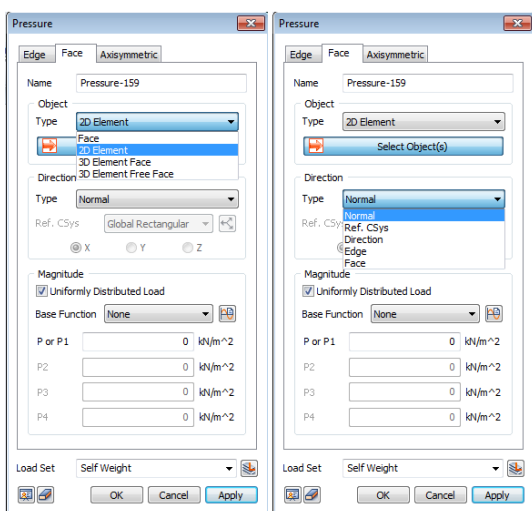


Fig. (1): Explanation of create the pressure

2.3 Construction Stage

The construction processes of shield TBM were simulated using a step-by-step approach. Construction stages contained 47 phases that have been established including the initial phase. Once construction stage is carried out (two segments of 1 m width are installed in one calculation step). The tunneling process starts by excavating the length of first lining ring and continues by pushing TBM forward till the length of last ring, which has been supported using concrete segments. Simultaneously, the process of grouting is injected into the cave between rock mass and tunnel liner. The static loads that applied do not act at the same time. Therefore, it will be described in which stage and what type of load is acting. Each of these stages is important and has different activity therefore the stages have to be modeled separately. After the initial stresses have been obtained from the initial conditions, the construction of loading and pressure types are applied. The structural changes and loading from the previous stage affects the next stage analysis results.

2.4 Boundary Conditions

The boundary conditions were consisted fixed displacements in the horizontal, vertical and the model bottom as illustrated in Figs. 2. To create constraint conditions, the target mesh of the tunnel and rock mass in 3-D, is automatically generated. The model is created as a cube and the model top or the ground surface was free to move. The x direction displacement constraint refers to the left/right side, the y direction displacement constraint refers to the front/back side and the x-y plane displacement constraint refers to the bottom of a model.

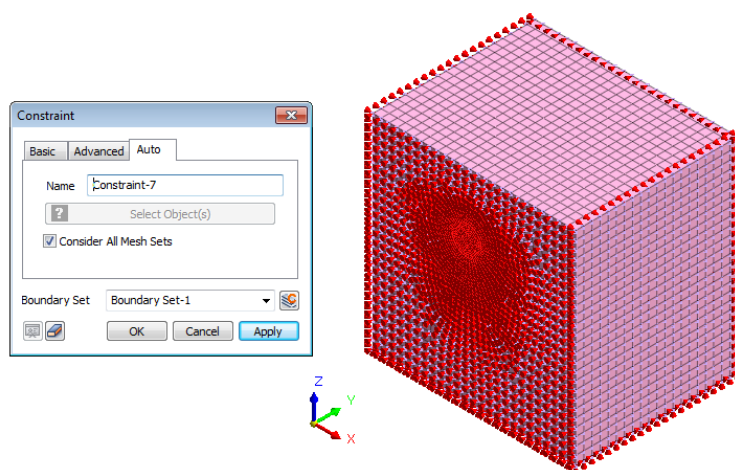


Fig. (2): Boundary condition (constraint conditions) was created, represented a static state

2.5 Simulation of the Numerical Model

The excavation and tunnel liner that is carried out using 3-D shield TBM method is required to get a more realistic results comparing to the 2-D modeling. The rock mass and segmental lining are modeled as solid elements. Concurrently, the shield and grout are modeled as shell elements. Reset clear displacement condition was applied to the first construction stage that will be considered as the in-situ condition. Numerical simulations of static analysis including the input data, mesh generation, boundary conditions, applied static loads, changing properties, applied all construction stages. The employ of water

pressure and consolidation problems is not taken into account. The tunnel lining is assumed as continuous solid elements were modelled as a concrete segment without considering the joints and bolts in the calculation (Fig. 3). The results of numerical models can be simulated the tunnel lining and the surrounding rock under combined conditions to predict the stress and deformation. The mesh size of 1 is used for tunnel structure; the 'Hybrid Mesher' is chosen to get a high quality mesh with less number of elements (MIDAS Information Technology). Fig. 4 shows the 3D view of developed shield TBM and its components.

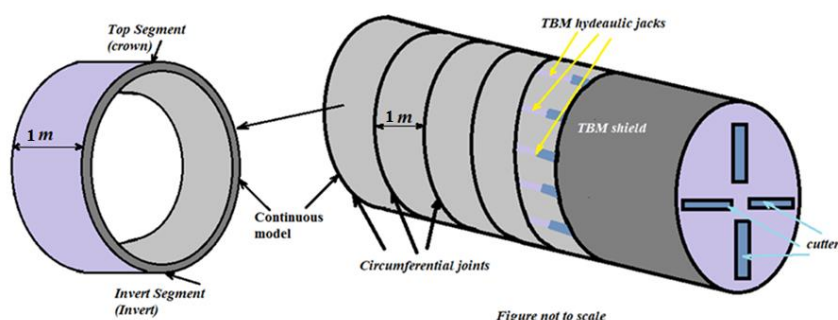


Fig. (3): Tunnel boring machine and segmental tunnel lining.

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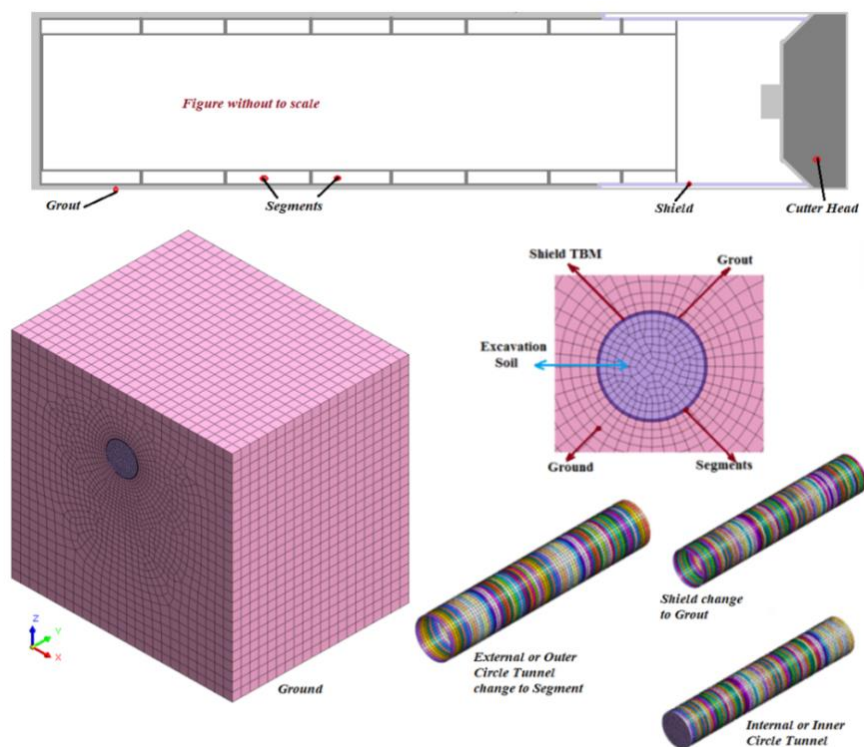


Fig. (4): Schematic of 3D shields TBM simulation

3. RESULTS

3.1 Displacement

The distribution of displacement including the maximum and minimum values in 2-D and 3-D view is illustrated in Figs. (5-7). The maximum value of total displacement is about 0.3 m due to the construction loads as shown in Fig.5. The displacement distribution (ovalization) including the maximum values in Z-direction is illustrated in Fig.9. The uneven distribution of the total displacement along the tunnel is due to the construction stages, the injection pressures and other technological loading. Total displacement distribution around tunnel has

diameter equal 14 m is occurred at the mid right side of segment # 35 as presented in Fig. 7. The final results of tunnel deformation and the surrounding rock mass are presented in Fig.14. In general, the ovalization is equal to the value of the diameter difference before and after deformation and it depends on the material stiffness also, it also decreases with increasing material stiffness. This phenomenon leads to change the shape of the deformed segment rings from circular to oval. Figs.8 and 9 shows typical displacement results of the tunnel under loading in both deformed and undeformed visualization schemes.

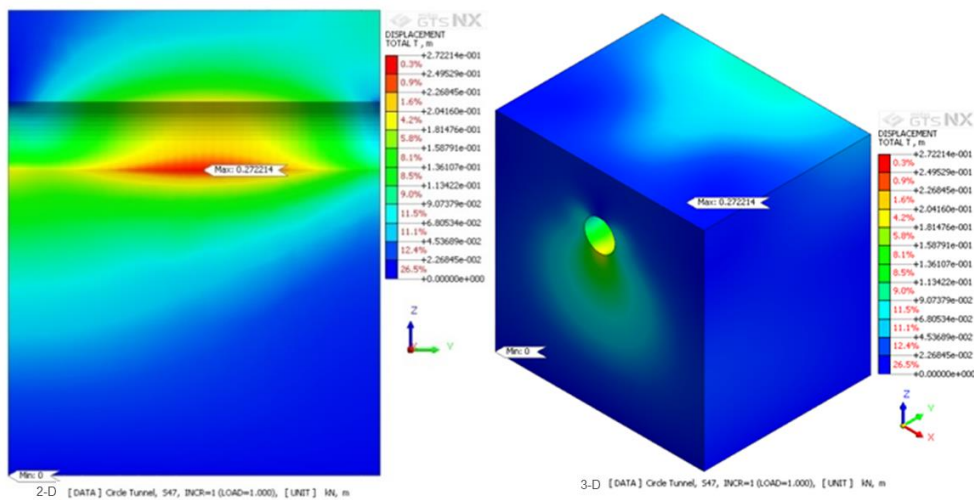


Fig. (5): A cross-section and 3-D modeling of total displacement [m] distribution, including the maximum value, tunnel with a diameter 14 m.

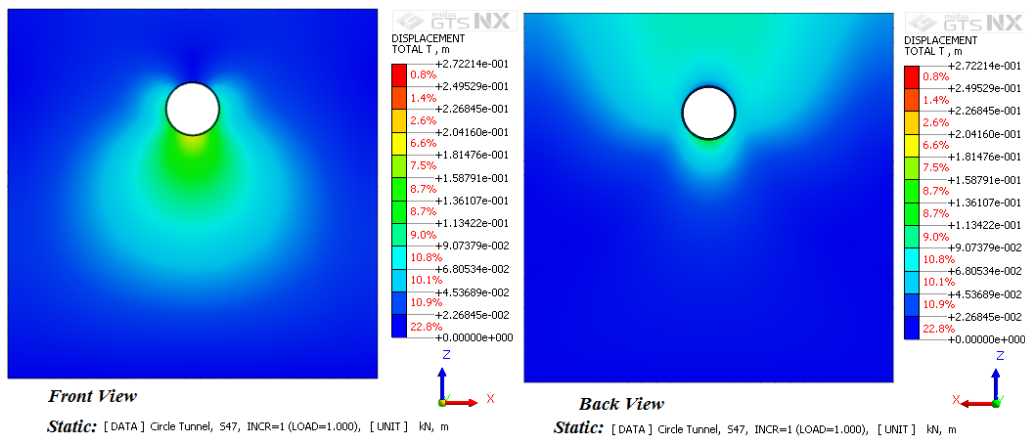


Fig. (6): A 2-D view modeling of total displacement [m] distribution, including the maximum value, tunnel has diameter 14 m.

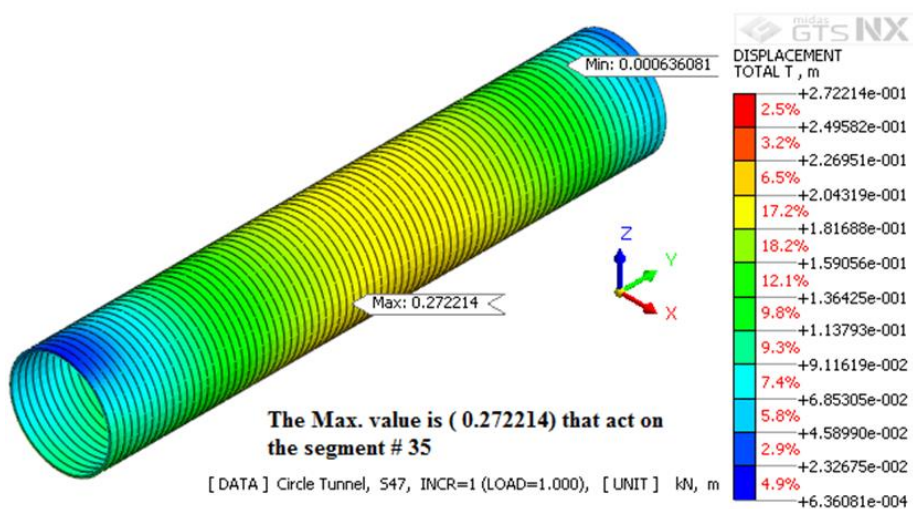


Fig. (7): A 3-D modeling of total displacement [m] distribution, including the maximum value, tunnel has diameter 14 m.

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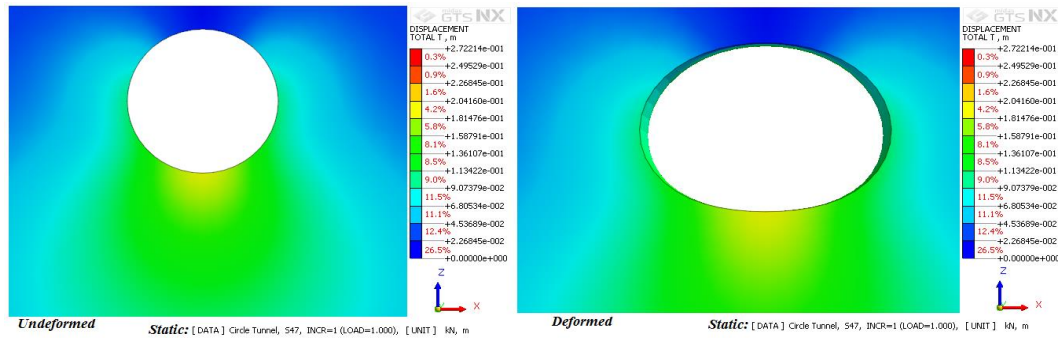


Fig. (8): A two dimensional view of ovalization [m] for total displacement, tunnel had diameter 14 m.

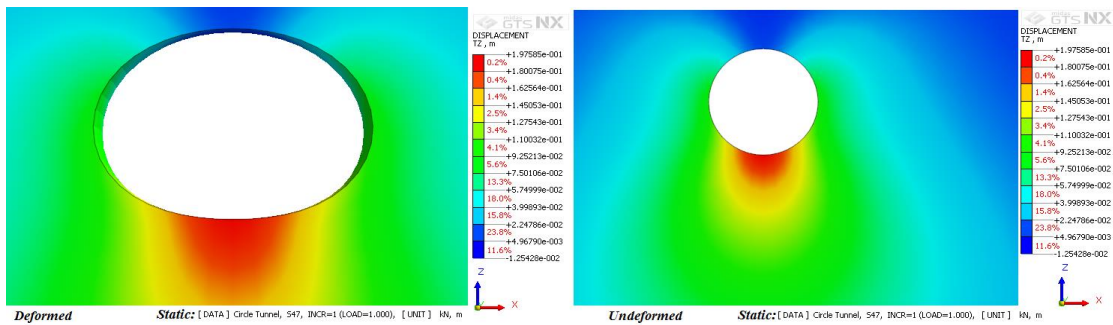


Fig. (9): A two-dimensional view of ovalization [m] for displacement in Z-direction, for tunnel had diameter 14 m.

3.2 Stress Distribution

The distribution of principal stresses (tensile and compressive) including the maximum value, that acts on the tunnel lining and the surrounding rock in 3-D models and 2-D view are illustrated in Figs. (10–13). Fig.10 shows the distribution for both tensile and compressive stresses for the tunnel with 14 m diameter and 80 m length. The maximum value of tensile stress is 224 MPa measured at the invert center of the first segment,

due to the high deformation (uplift in the invert). The value of compressive stress in this figure is about 0.3 MPa at the mid right side of segment # 76. The maximum value of compressive stress is 34 MPa measured at the mid right side of segment # 73 for the tunnel with 14m diameter as illustrated in Fig.12. The maximum and minimum principal stresses distributions that act on rock mass are shown in Figs. 11 and 14.

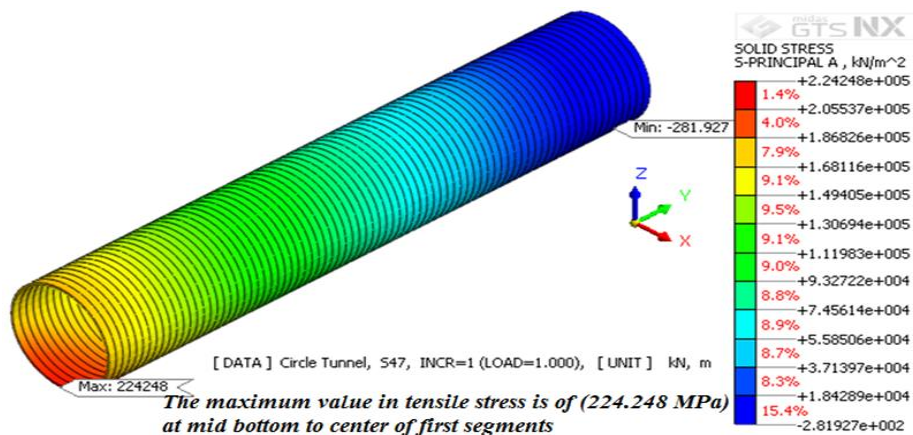


Fig. (10): A 3-D modeling of Max. principal stresses [kN/m²] distribution, including the maximum value, tunnel with a diameter 14 m.

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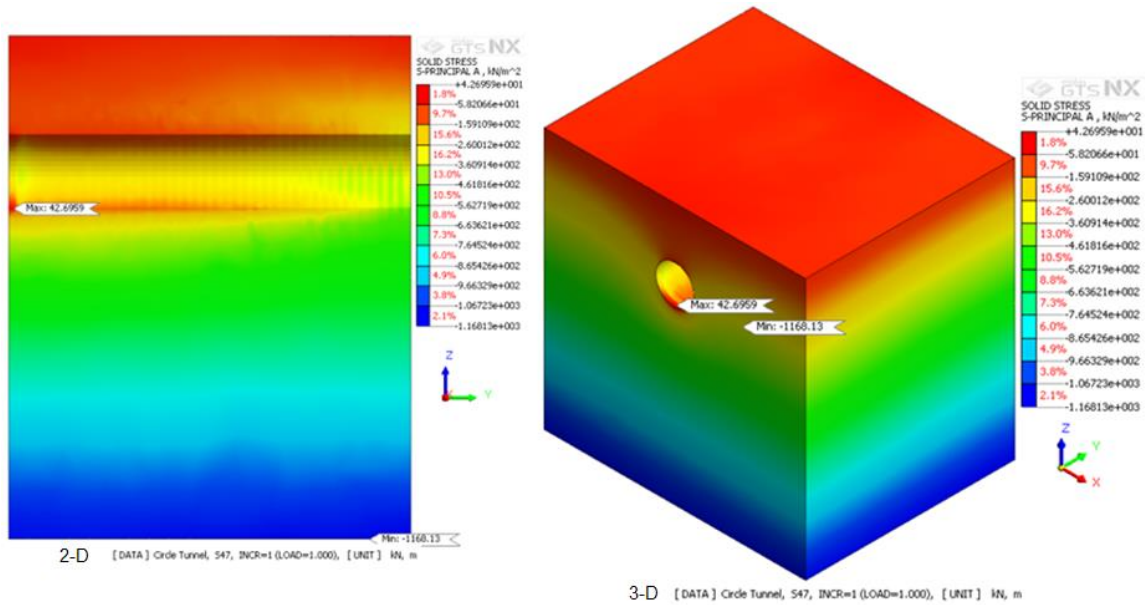


Fig. (11): A cross-section and three-dimensional view of Max. principal stresses [kN/m²] distribution, including the maximum value, tunnel has diameter 14 m.

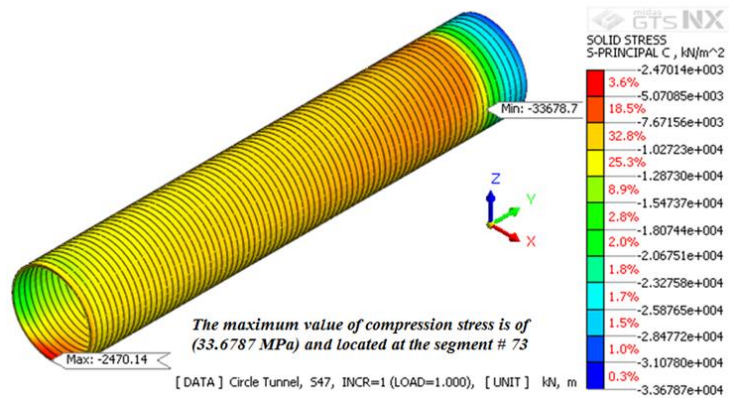


Fig. (12): The compressive stresses in the maximum and minimum value, which were obtained around the tunnel has diameter 14 m.

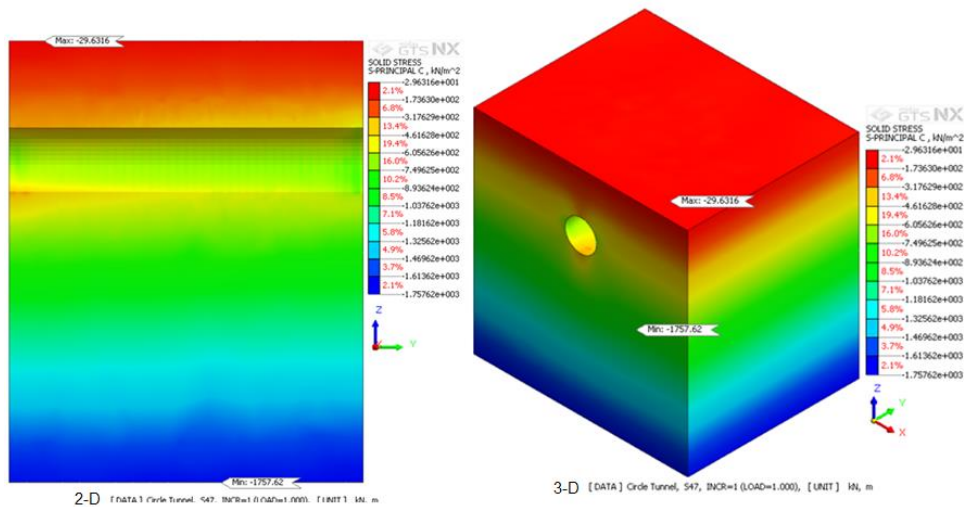
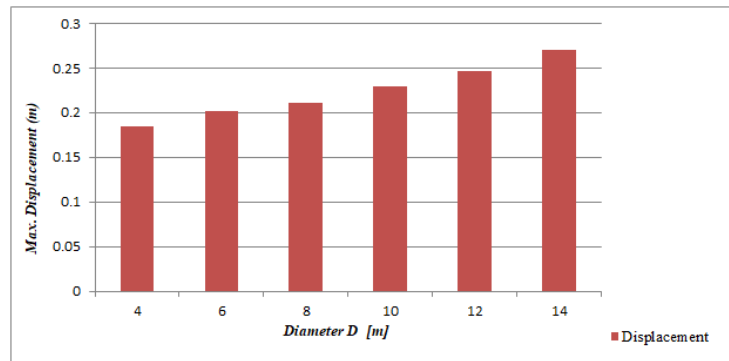


Fig. (13): A cross-section and three-dimensional view of Min. principal stresses [kN/m²] distribution, including

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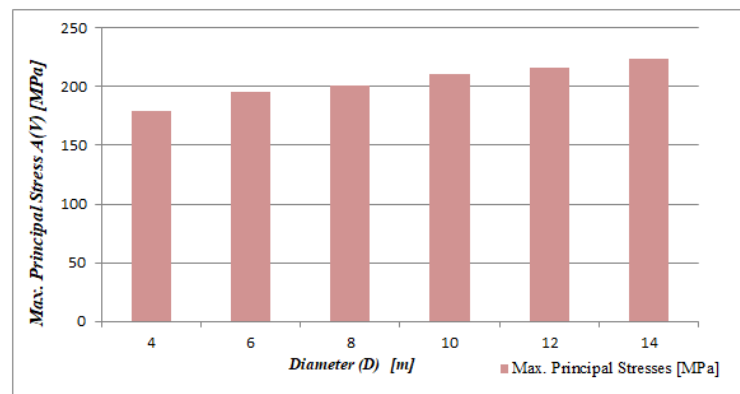
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the maximum value, regarding static and dynamic analysis for tunnel had diameter 14 m, within the first category of soft rock medium.



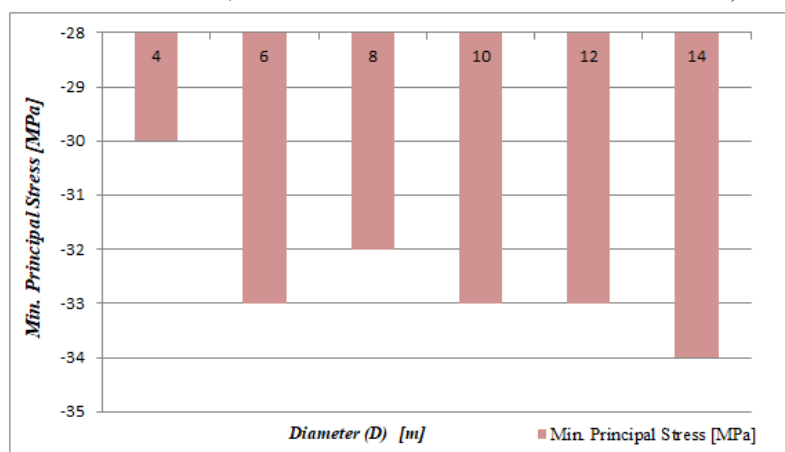
Cases	Tunnel Diameter (D) [m]						Segment #
	4	6	8	10	12	14	
Displacement [m]	0.200465	0.2197	0.227021	0.242783	0.254706	0.272214	35

Fig. (14): Calculated the Max. value of total displacement [m] distribution for all tunnel diameter.



Cases	Tunnel Diameter (D) [m]						Segment #
	4	6	8	10	12	14	
Max. Principal Stresses [MPa]	179	196	201	211	216	224	1

Fig. (15): Calculated the maximum principal stresses [MPa] distribution for all tunnel diameters (Based on the table, the tensile stresses within all tunnel diameters).



Cases	Tunnel Diameter (D) [m]						Segment #
	4	6	8	10	12	14	
Min. Principal Stress [MPa]	-30	-33	-32	-33	-33	-34	73

Fig. (16): Calculated the minimum principal stresses [MPa], for all tunnel diameter (Based on the table, the compressive stresses within all tunnel diameters).

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Table (4): The Max. value from the results that act on the segmental lining regarding static analysis.

Analysis	Static state		
	Value	D = [m]	Segment #
Max. Displacement [m]	0.3	14	35
Max. Principal Stress [MPa]	224	14	1
Min. Principal Stress [MPa]	- 34	14	73

The negative sign (represents as" -") refers to compressive stress

4. CONCLUSIONS

The methodology of numerical approach to analysis the behaviour of circular tunnel and surrounding rock mass exposed to the static loading is described. The major parameters that are used in this study are tunnel diameters (D), elastic modulus (E) and Poisson's ratio (ν) of rock mass, unite weight (γ) and construction loads. The results are compared in terms in of displacement (total displacement) and principal stresses. It is observed that deformation in the tunnel lining and the surrounding rock mass depends on the several parametric including the tunnel diameters, types of rock mass, elastic modulus of rock mass, and tunnel depth from the ground surface. Determination of the magnitude and direction of principal stresses in the lining have been evaluated. It is concluded that the stresses and displacement are affected by the diameter of tunnels. The increase in diameter leads to an increase in the normal forces by increasing pressure on the lining. The result of this analysis approved that the lining of large tunnel diameter is more affected by stresses and deformation than lining supporting tunnel with lower diameter. The deformation of the horizontal direction perpendicular to the longitudinal tunnel axis is larger than the vertical direction due to the additional loads in vertical direction e.g. the self-weight. The construction load affects the stresses inside the tunnel lining also and can lead to the high deformation. The

results approved that lining of tunnel with large diameter is exposed to more stresses and deformation. The final results of the analysis are illustrated in the Figs. 14-16 and Tables 4.

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